Rare Kaon Decays

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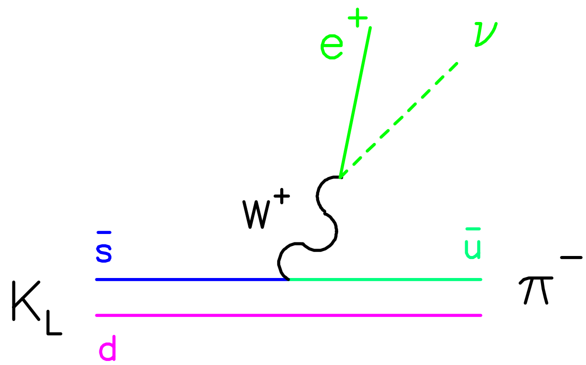
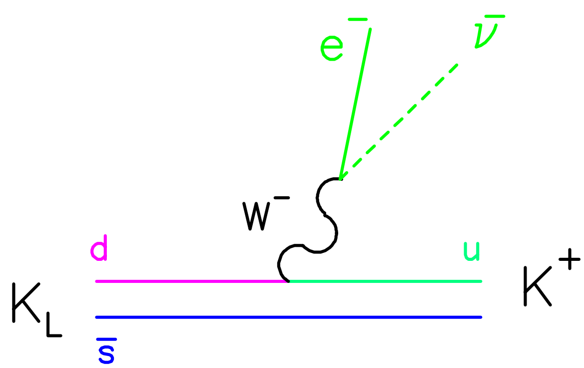
XXXVth Rencontres de Moriond - March 2000

What makes decays rare?

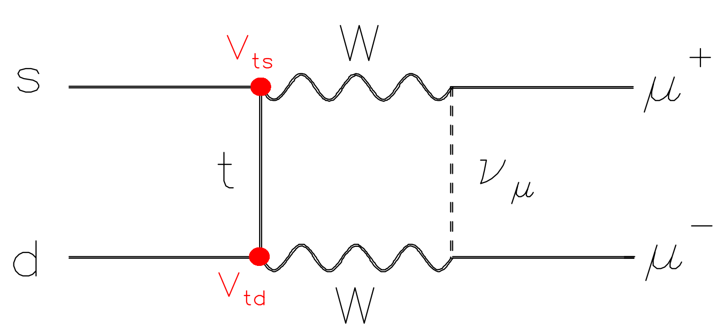
Common decay:



Rare by virtue of kinematics:



Rare since suppressed to 2nd order:



Rare K decay modes studied recently

$K^+ \to \pi^+ \nu \bar{\nu}$
$K_L \to \pi^0 \mu^+ \mu^-$
$K^+ \to \pi^+ \mu^+ \mu^-$
$K_L \to \mu^+ \mu^-$
$K^+ \to \pi^+ e^+ e^- \gamma$
$K_L \to e^\pm e^\mp \mu^\pm \mu^\mp$
$K_L \to \pi^+ \pi^- \gamma$
$K^+ \to \pi^+ \pi^0 e^+ e^-$
$K_L \to \pi^0 \gamma \gamma$
$K^+ \to \mu^+ \nu \gamma$
$K^+ \to \mu^+ \nu e^+ e^-$
$K_L \to e^+ e^- \gamma$
$K_L \to e^+ e^- \gamma \gamma$
$K_L \to e^+ e^- e^+ e^-$
$K^+ \to \pi^+ \mu^+ e^-$
$K_L \to \mu^\pm e^\mp$
$K^+ \to \pi^- e^+ e^+$
$K^+ \to \pi^+ X^0$

$K_L \to \pi^0 \nu \bar{\nu}$
$K_L \to \pi^0 e^+ e^-$
$K^+ \to \pi^+ e^+ e^-$
$K_L \to e^+ e^-$
$K^+ \to \pi^+ \pi^0 \nu \bar{\nu}$
$K^+ \to \pi^+ \pi^0 \gamma$
$K_L \to \pi^+ \pi^- e^+ e^-$
$K^+ \to \pi^0 \mu^+ \nu \gamma$
$K^+ \to \pi^+ \gamma \gamma$
$K^+ \to e^+ \nu e^+ e^-$
$K^+ \to e^+ \nu \mu^+ \mu^-$
$K_L \to \mu^+ \mu^- \gamma$
$K_L \to \mu^+ \mu^- \gamma \gamma$
$K_L \to \pi^0 e^+ e^- \gamma$
$K_L \to \pi^0 \mu^\pm e^\mp$
$K^+ \to \pi^- \mu^+ e^+$
$K^+ \to \pi^- \mu^+ \mu^+$
$K_L \to e^\pm e^\pm \mu^\mp \mu^\mp$

Motivation for Rare K Decay Experiments

Forbidden

S.M. forbids (or greatly inhibits) many kinematically possible modes

A number of these are allowed (or enhanced) by alternative approaches

Accessible sensitivity to these processes corresponds to very high mass scales

Discouraged

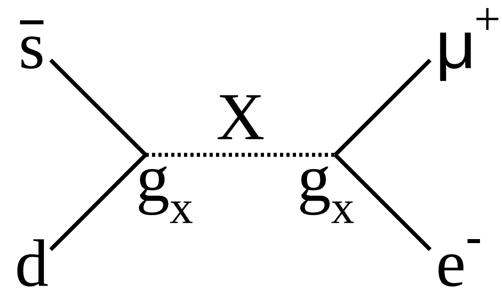
Certain very inhibited processes cleanly sensitive to S.M. parameters

Tolerated

Suppressed processes are a good area for testing chiral perturbation theory and other approaches to understanding the low energy structure of the S.M.

Lepton Flavor Violation

Poster child for sensitivity to BSM processes such as $\rightarrow$ Attainable sensitivity corresponding to $M_X \gtrsim 100\text{TeV}$, clean signatures



Current status:

Process	90% CL Limit	Experiment	Reference
$K_L \to \mu e$	4.7×10^{-12}	AGS-871	PRL 81:5734
$K^+ \to \pi^+ \mu^+ e^-$	2.9×10^{-11}	AGS-865	M. Zeller K-99
$K_L \to \pi^0 \mu e$	3.1×10^{-9}	FNAL-799	PL B432:230

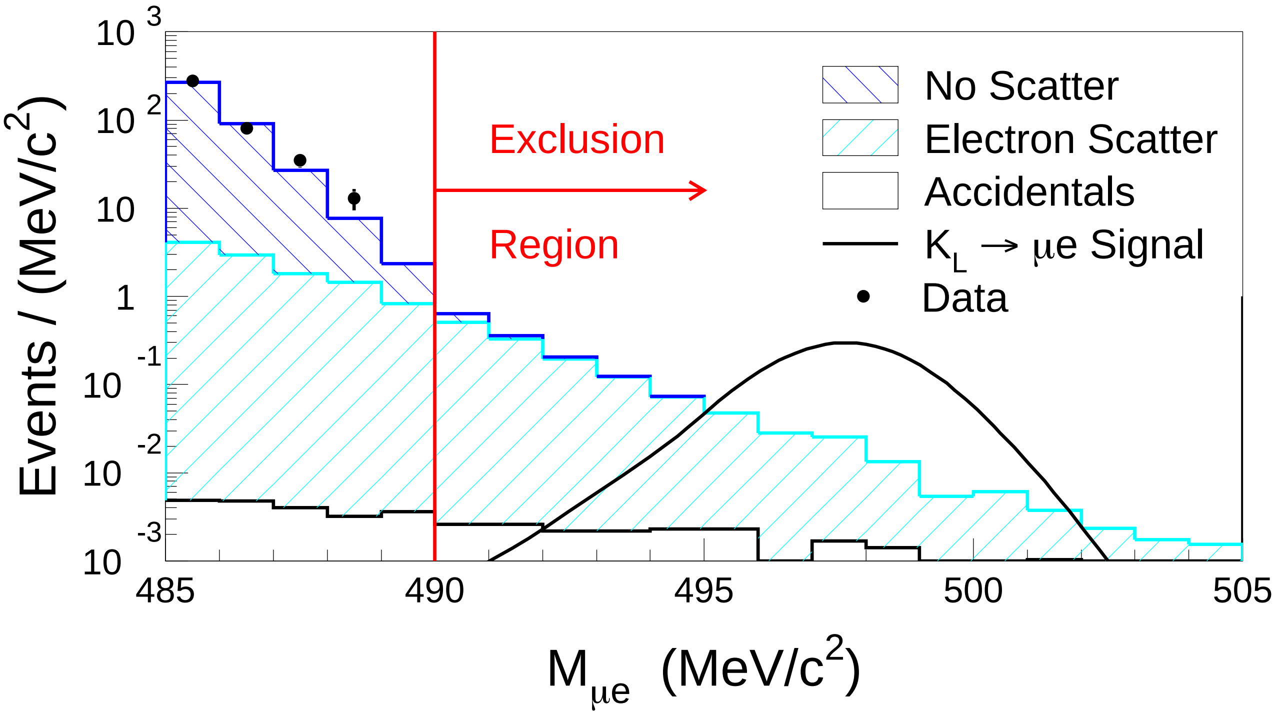
More data on the last two of these is on the way as is data on other LFV modes (e.g. $K^+ \to \pi^+ \mu^- e^+$).

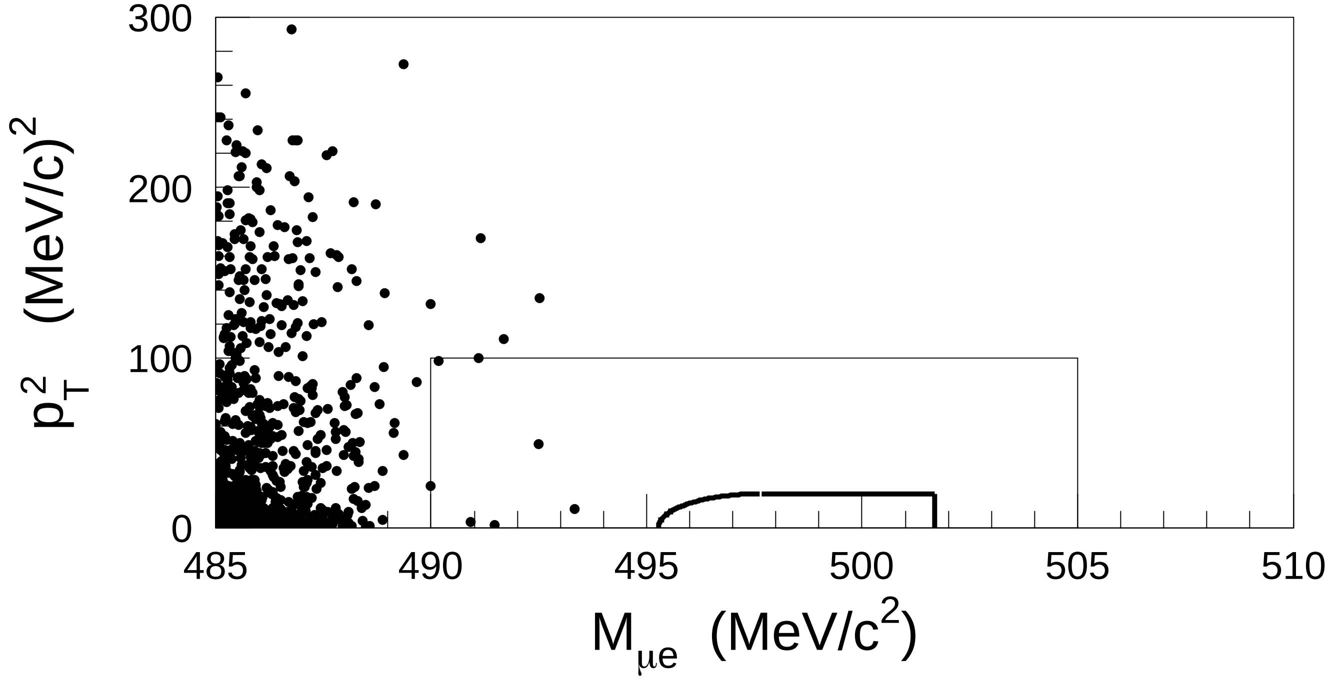
A long list of BSM theories predict LFV in K decays at some level, e.g. extended technicolor, SUSY, heavy neutrinos, horizontal gauge bosons, etc. Also necessary to study both two and three body decays to check Lorentz structure of any new interaction, generation number sensitivity, etc.

But these experiments have already helped kill the most promising approaches that predicted finite effects.

It is likely that after the current round of experiments, future information will come as by-product of other studies.

E871 Search for $K_L \to \mu e$





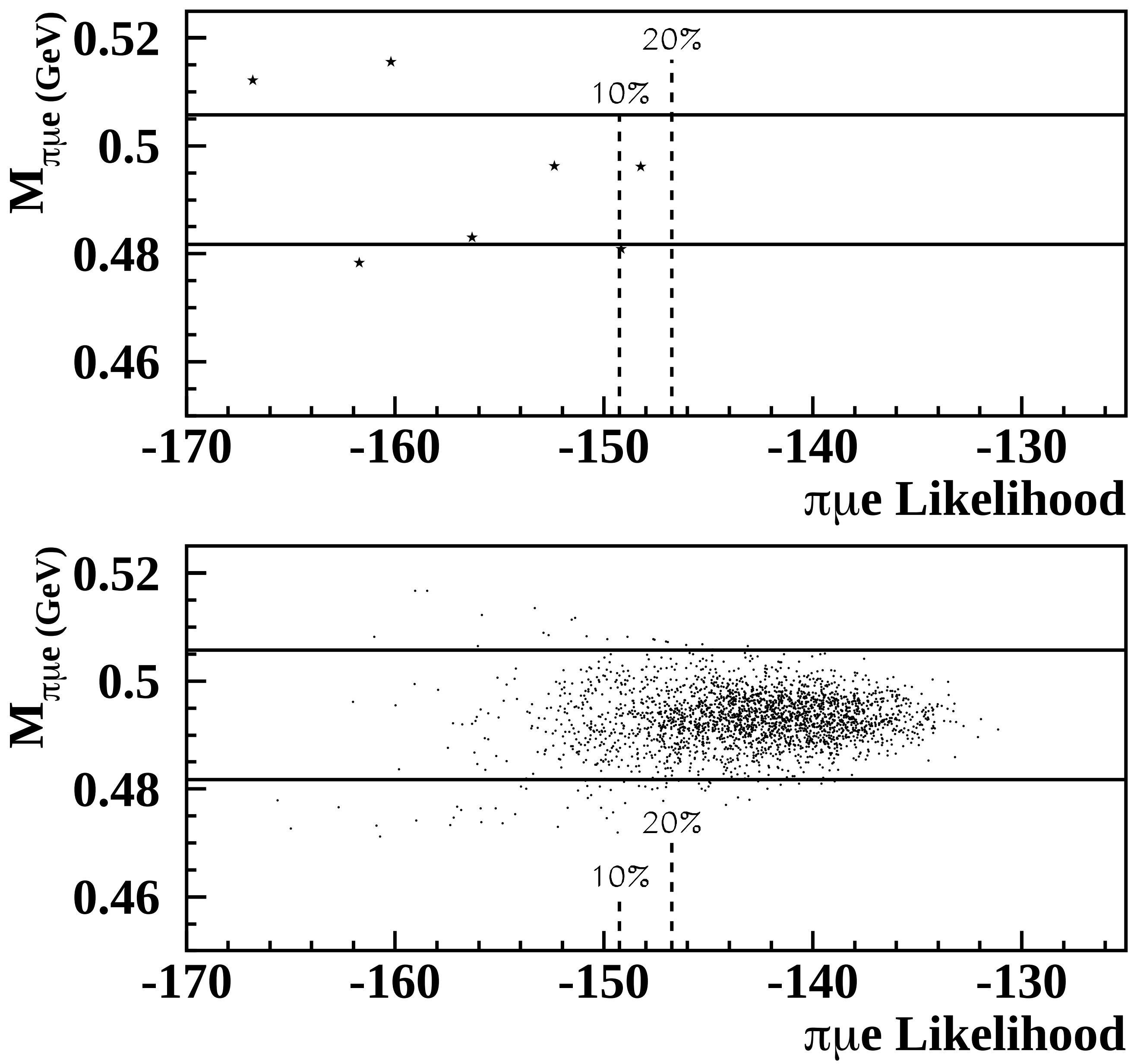
No events observed, expected background ~ 0.1 events

Yields $B(K_L \to \mu e) < 4.7 \times 10^{-12}$ at 90% c.l.

Would be difficult to get another O.M. due to Mott scattering

Limit corresponds to $M > 150\text{TeV}$ for HGB!

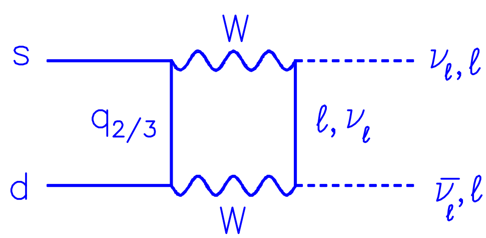
E865 Search for $K^+ \to \pi^+\mu^+e^-$

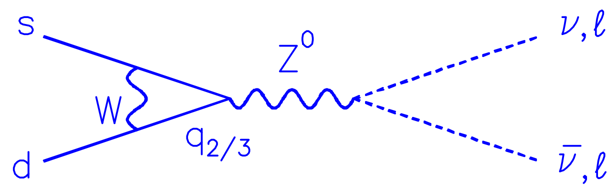


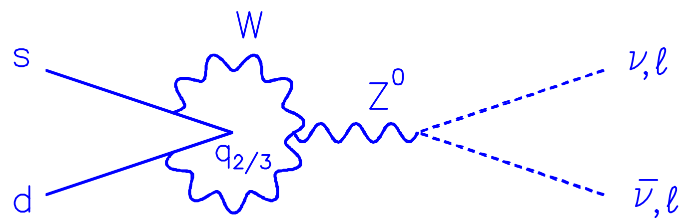
1996 sample yields (at 90% c.l.): $B(K^+ \to \pi^+\mu^+e^-) < 4.0 \times 10^{-11}$
+ previous data of this series of experiments: $< 2.9 \times 10^{-11}$
Expected limit including all data: $< 7.0 \times 10^{-12}$

One-loop K Decays

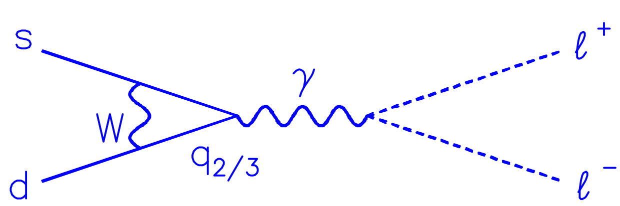
Short-distance contributions to K decays. These decays include $K_L \to \pi^0 \nu\bar{\nu}$, $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \mu^+\mu^-$, $K_L \to \pi^0 e^+ e^-$, $K_L \to \pi^0 \mu^+\mu^-$, etc. The hadronic matrix elements involved are known from common decays such as $K^0 \to \pi^+ e^- \bar{\nu}$. These contributions can be cleanly calculated in terms of m_t, m_c and the product of CKM elements $V_{ts}^* V_{td} \equiv \lambda_t$.





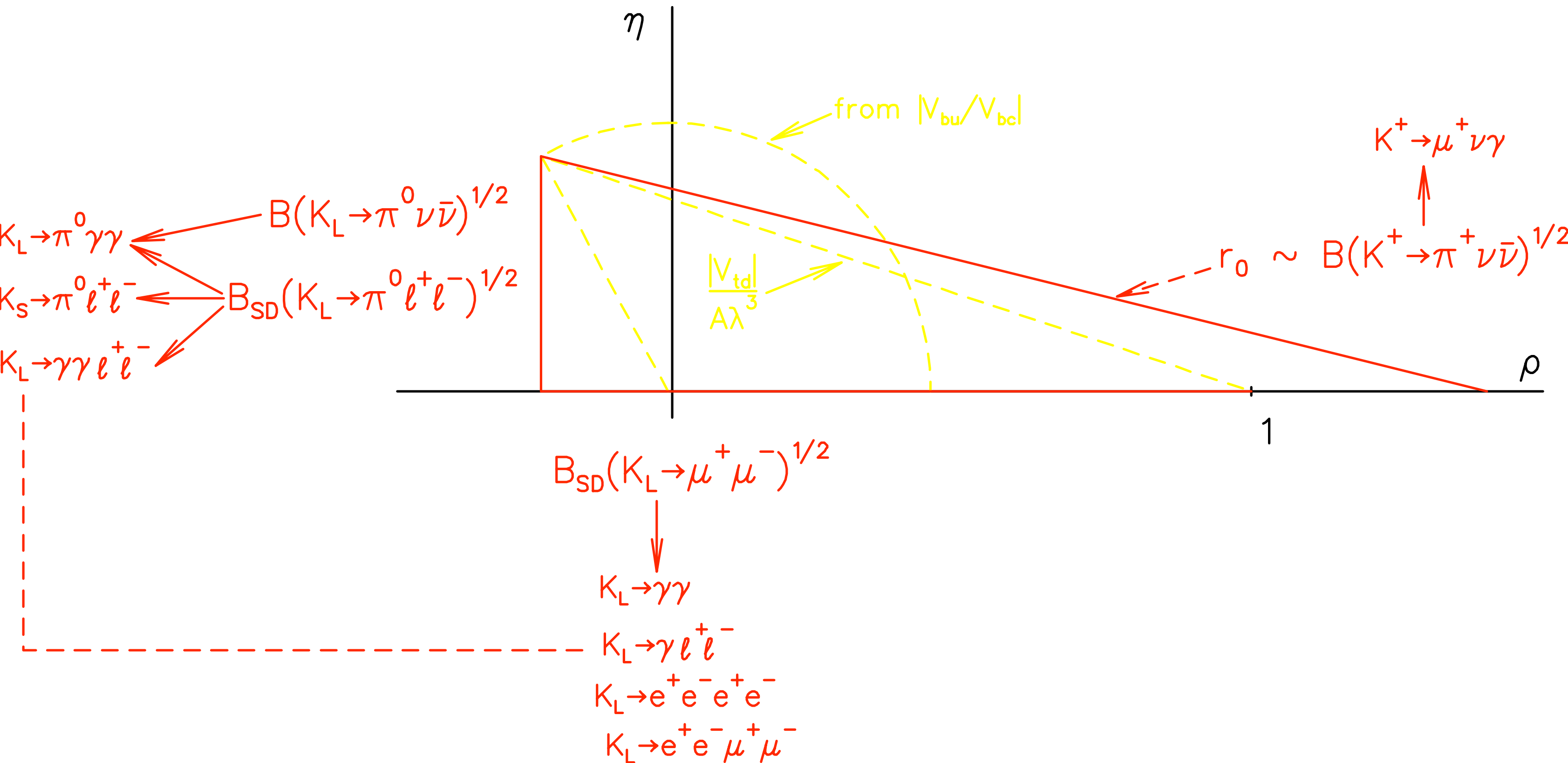


But there's a Murphy's Law for these processes:
The same interactions that allow charged final state leptons to be detected, mediate long-distance contributions. E.g.:



To avoid this one must exploit decays containing a $\nu\bar{\nu}$ pair.

Rare K Decay and the Unitarity Triangle



$\underline{K_L \to \mu^+\mu^-}$

The short distance part of $B\left(K_L \to \mu^+\mu^-\right)$ given by:

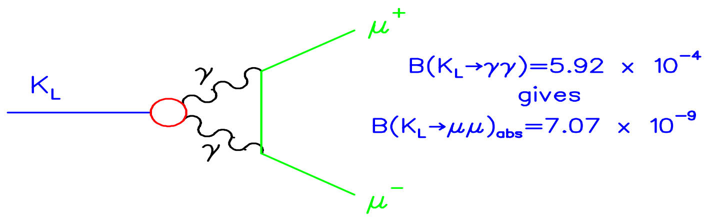
$$B^{SD}_{\mu\mu} = \frac{\tau_{K_L}\alpha^2 B_{K^+\mu\nu}}{\tau_{K^+}V_{us}^2\pi^2 sin^4\theta_W}\left[Re\left(\lambda_c\right)Y_{NL} + Re\left(\lambda_t\right)Y\left(x_t\right)\right]^2 \approx \mathcal{O}\left(10^{-9}\right)$$

where $Re\left(\lambda_c\right) = \lambda\left(\frac{\lambda^2}{2} - 1\right)$; $\lambda \equiv sin\theta_{Cabibbo}$

To a good approximation $Y\left(x_t\right) = 0.32\left(m_t/m_W\right)^{1.56}$

$Y_{NL} \approx 3 \times 10^{-4}$

But this is dominated by an absorptive contribution from:



much larger than the dispersive part.

If precise measurements are made, this can be subtracted

But there is also a long distance contribution to the real part
This can interfere with the short distance contribution
To untangle, must know $A\left(K_L \to \gamma\gamma\right)$ with γs off mass-shell
- size, calculability controversial

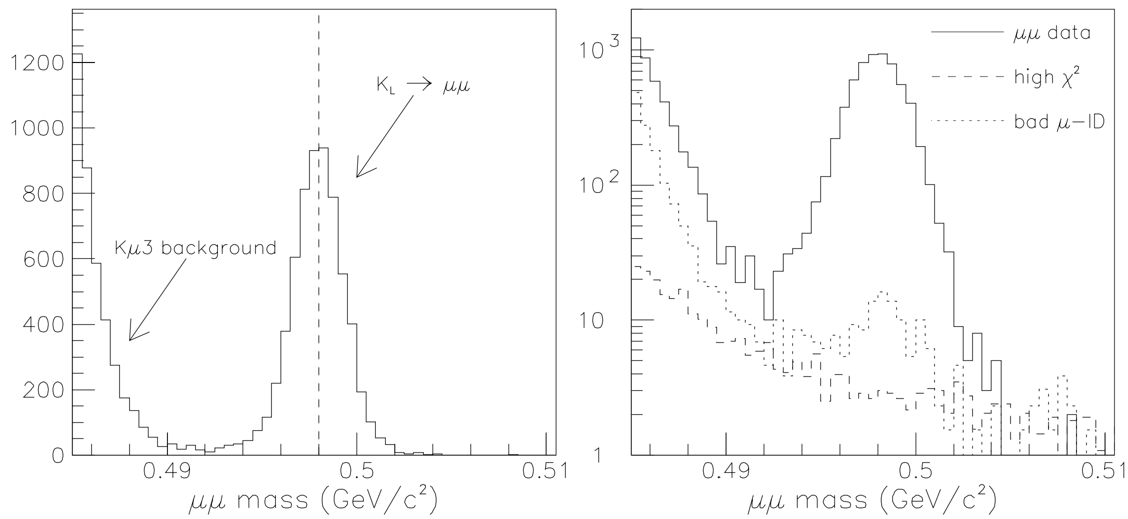
Can we **measure** this?

There are recent or forthcoming results on:

$K_L \to ee\gamma$
$K_L \to \mu\mu\gamma$
$K_L \to eeee$
$K_L \to ee\mu\mu$

Whether even this can help is still controversial

E871 Measurement of $K_L \to \mu^+\mu^-$



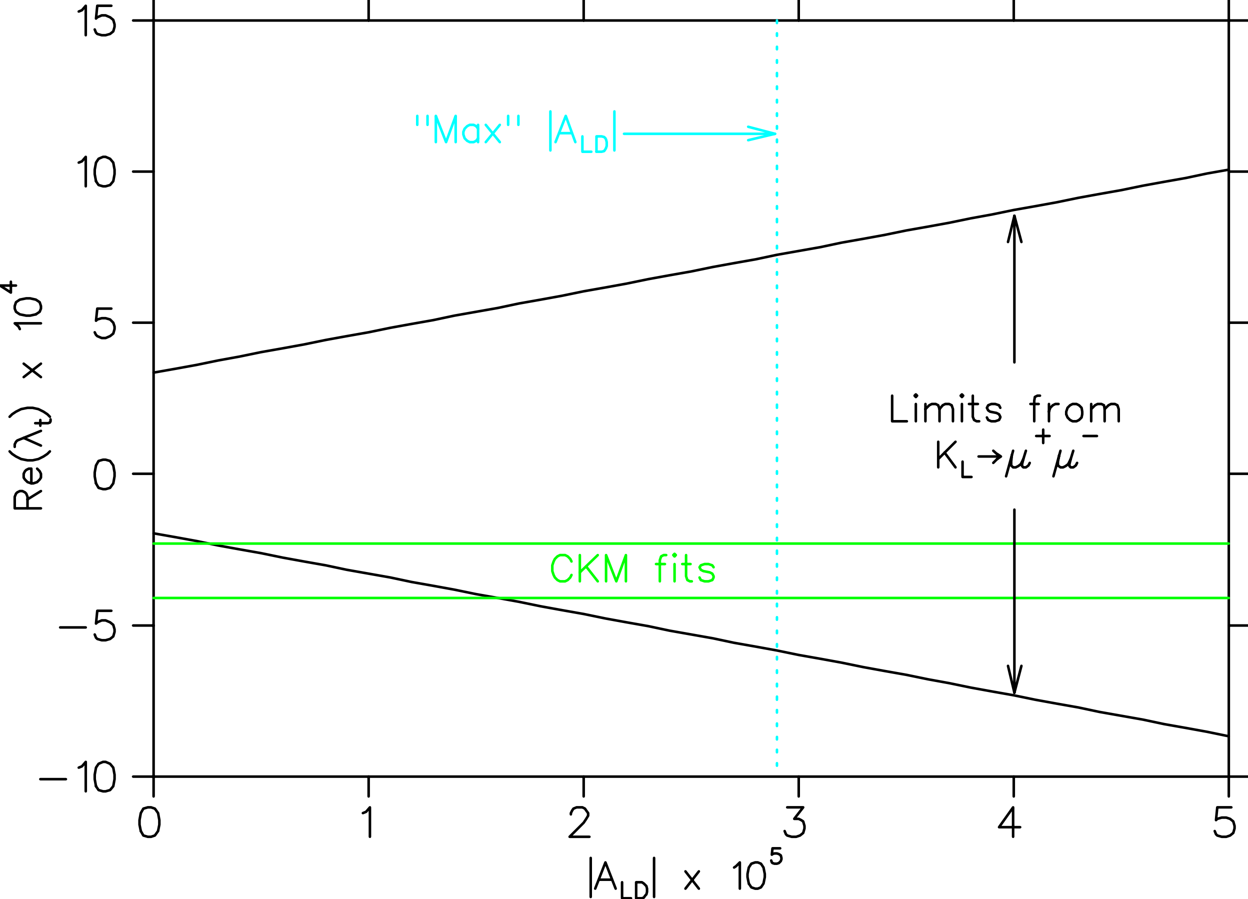
AGS-871 has observed more than 6200 $K_L \to \mu^+\mu^-$ events

They obtain $B(K_L \to \mu^+\mu^-) = (7.18 \pm 0.17) \times 10^{-9}$
- a three-fold improvement in precision on this BR

To be compared with $B(K_L \to \mu^+\mu^-)_{abs} = (7.07 \pm 0.18) \times 10^{-9}$
which yields $B(K_L \to \mu^+\mu^-)_{disp} = (0.11 \pm 0.18) \times 10^{-9}$
or $B(K_L \to \mu^+\mu^-)_{disp} < 0.37 \times 10^{-9}$ at 90% c.l.

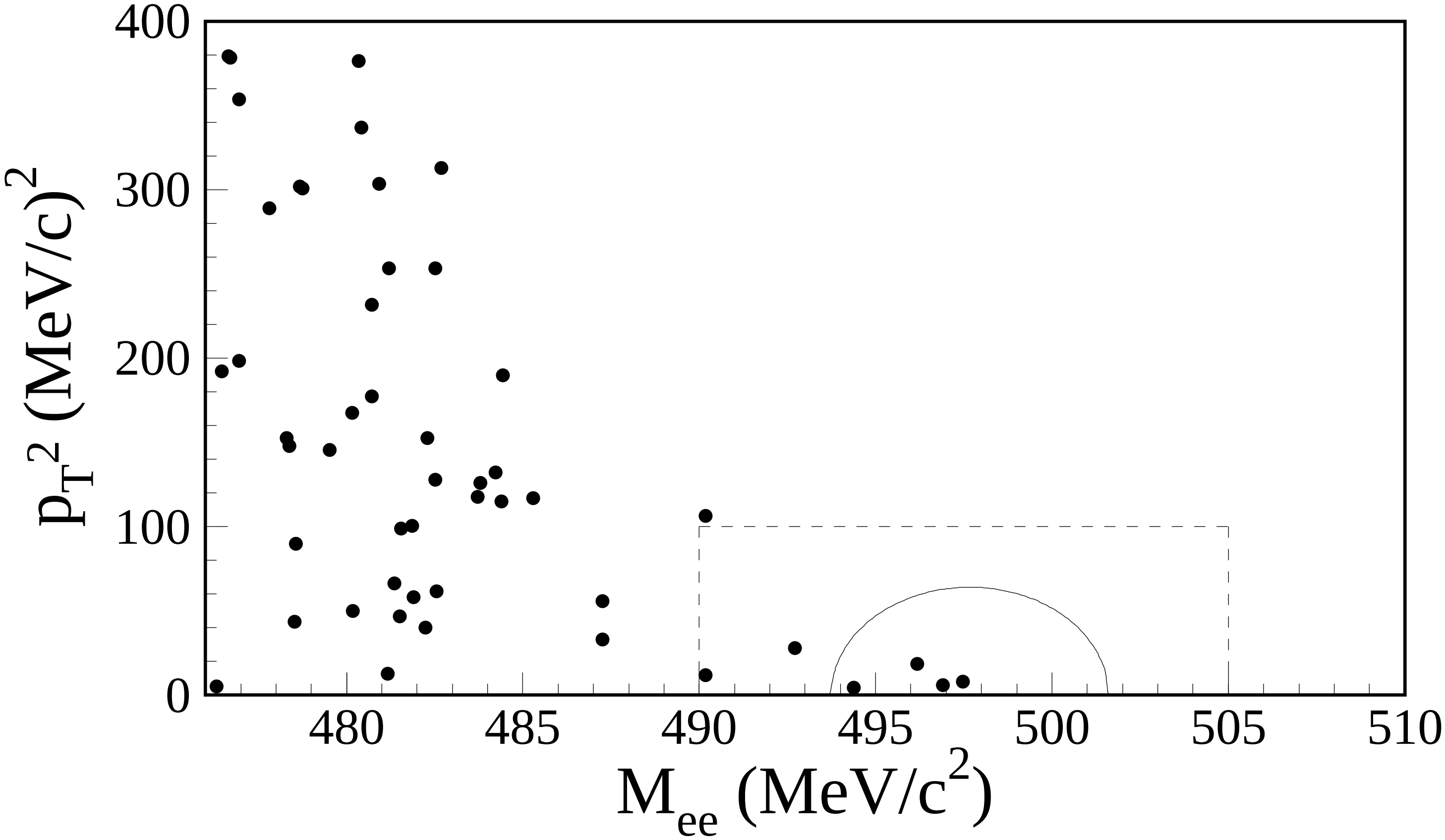
Potentially this bounds CKM ρ, or more directly, $Re(V_{ts}^* V_{td})$
But need a calculation of the long-distance dispersive piece
Somewhat controversial – see graph

This result seems to **require** a finite long-distance piece.



15
10
5
0
−5
−10
0
1
2
3
4
5
$\mathrm{Re}(\lambda_t) \times 10^4$
$|A_{LD}| \times 10^5$
"Max" $|A_{LD}|$
Limits from
$K_L \to \mu^+ \mu^-$
CKM fits

E871 Measurement of $K_L \to e^+e^-$



AGS-871 has observed four $K_L \to e^+e^-$ candidates with an expected background of 0.17 ± 0.10 events

They obtain $B(K_L \to e^+e^-) = (8.7^{+5.7}_{-4.1}) \times 10^{-12}$

This is the lowest BR ever measured

Unfortunately can't be used to get short distance information.

$\underline{K^+ \to \pi^+ \nu\bar{\nu}}$

$$B\left(K^+ \to \pi^+\nu\bar{\nu}\right) \;=\; \frac{r_{K^+}\alpha^2 B\left(K^+ e3\right)}{V_{us}^2 2\pi^2 sin^4\theta_W}\;\sum_l \left|\lambda_c X_{NL}^{\ell} + \lambda_t X\left(x_t\right)\right|^2 \approx 10^{-10}$$

$\uparrow$
contains QCD corr.
has been calc'd to NLLA

$X \approx 0.66\left(m_t/m_W\right)^{1.18}$

$$= 4.1 \times 10^{-11} A^4 X^2\left(x_t\right)\left[\bar{\eta}^2 + \tfrac{2}{3}\left(\rho_o^e - \bar{\rho}\right)^2 + \tfrac{1}{3}\left(\rho_o^\tau - \bar{\rho}\right)^2\right]$$

where $\rho_o^\ell \equiv 1 + \frac{X_N^\ell L}{A^2\lambda^4 X(x_t)}$; $r_{K^+} = 0.9$

$\uparrow$
calc. uncertainty only a few %

In leading order in Wolfenstein parameters,
$B\left(K^+ \to \pi^+\nu\bar{\nu}\right)$ determines a circle in the ρ, η plane with center $\left(\rho_o, 0\right)$; $\rho_o \equiv \frac{2}{3}\rho_o^e + \frac{1}{3}\rho_o^\tau \approx 1.4$ and radius $= \frac{1}{A^2}\sqrt{\frac{B(K^+\to\pi^+\nu\bar{\nu})}{10^{-10}}}$

Don't need to deal with Wolfenstein parameters, instead:

$$B\left(K^+ \to \pi^+\nu\bar{\nu}\right) = .00015\left[\left(\lambda_c\bar{X} + Re\left(\lambda_t\right)X\left(x_t\right)\right)^2 + \left(Im\left(\lambda_t\right)X\left(x_t\right)\right)^2\right]$$

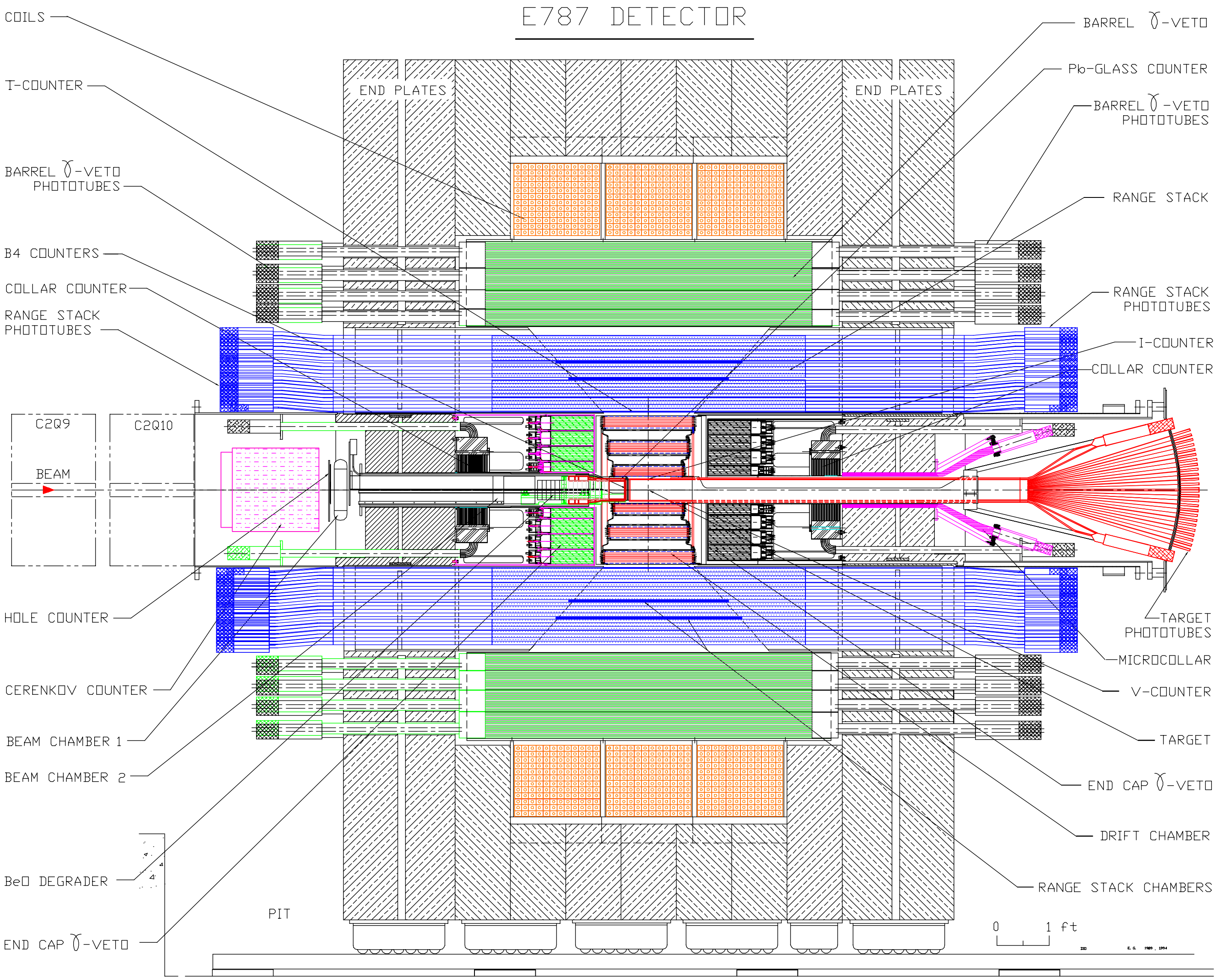
This gives a circle in the $Re\left(\lambda_t\right)$, $Im\left(\lambda_t\right)$ plane

From measurement of $B = \left(K^+ \to \pi^+\nu\bar{\nu}\right)$, can get limits
(tangents to circle)

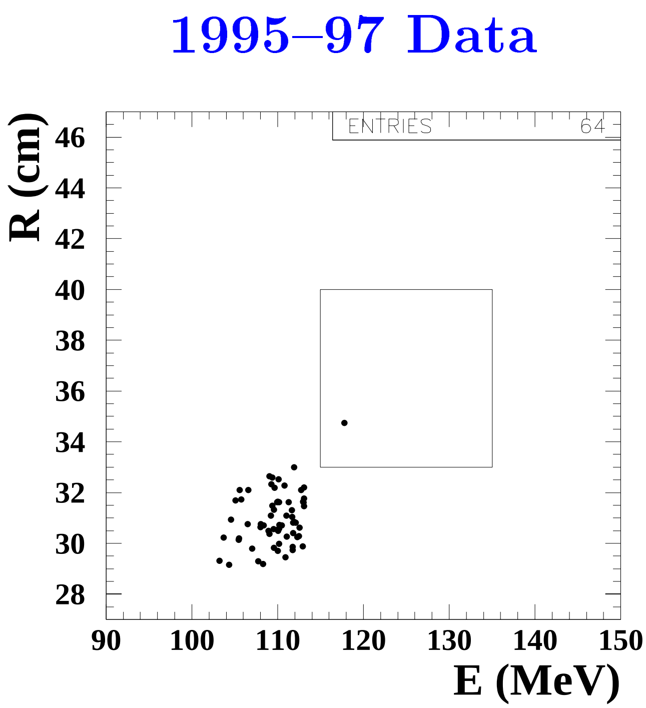
E787

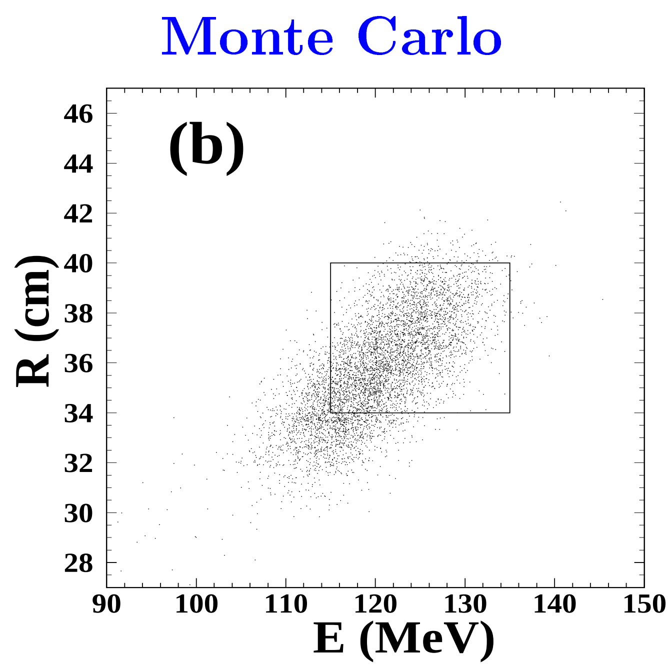
Study of $K^+ \to \pi^+ \nu\bar{\nu}$ and related processes

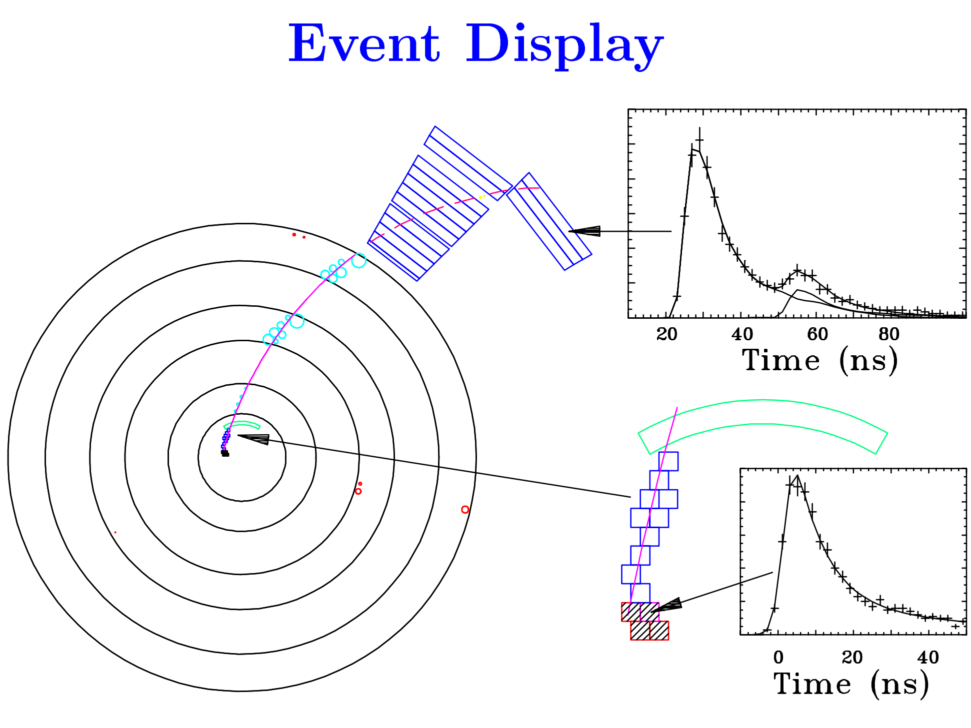
BNL/Fukui/KEK/Kyoto/Osaka/Princeton/TRIUMF



$K^+ \to \pi^+ \nu\overline{\nu}$ Event







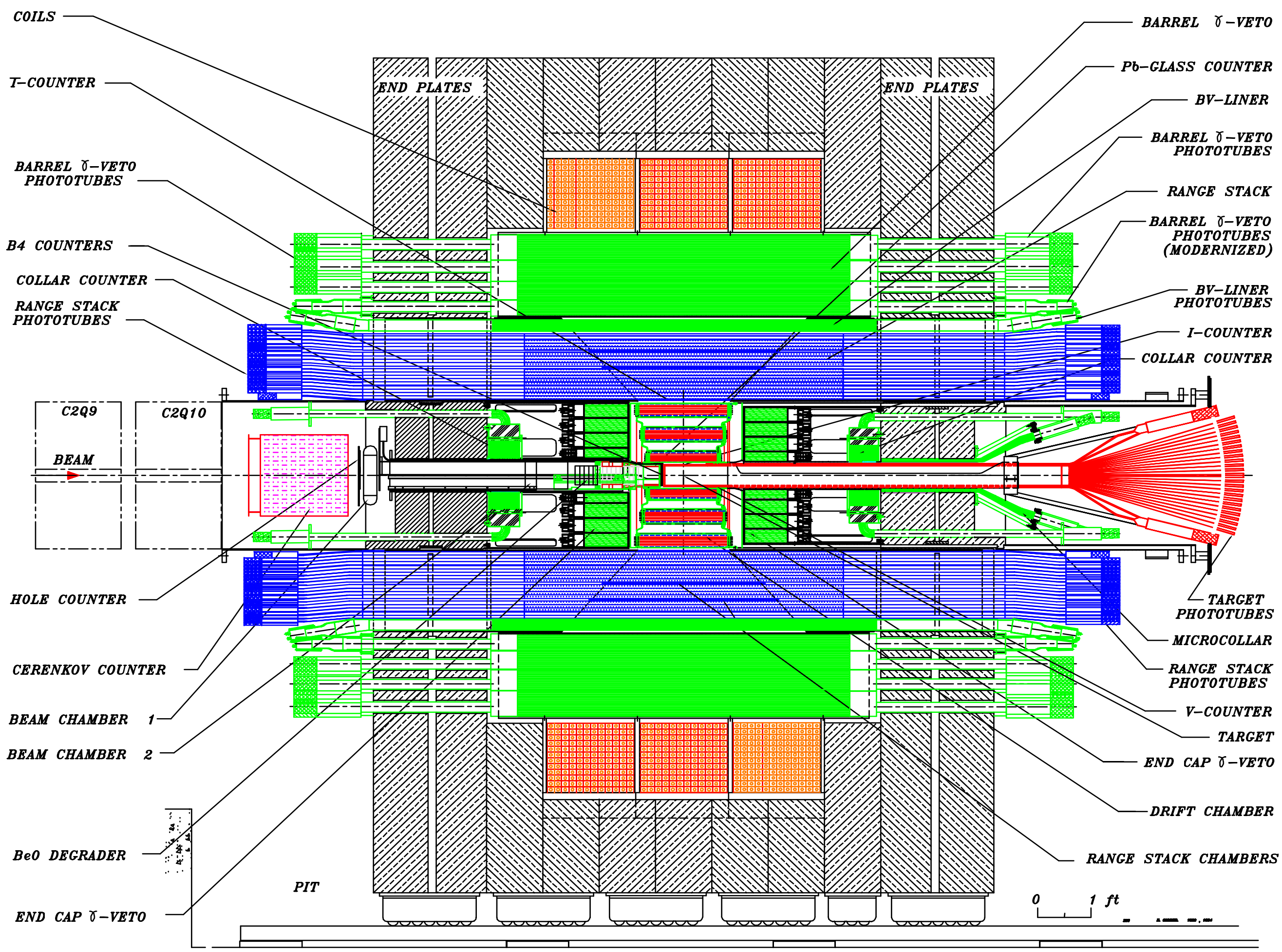
$$\mathbf{BR}(K^+ \to \pi^+ \nu\overline{\nu}\ ) = (1.5^{+3.4}_{-1.2}) \times 10^{-10}$$

(1995: PRL **79**, 2204, 1997, 1995–7: hep-ex/0002015)

E949 Measurement of $B(K^+ \to \pi^+ \nu \bar{\nu})$

E949

Alberta/BNL/FNAL/Fukui/INR/KEK/Kyoto/UNM/Osaka/TRIUMF

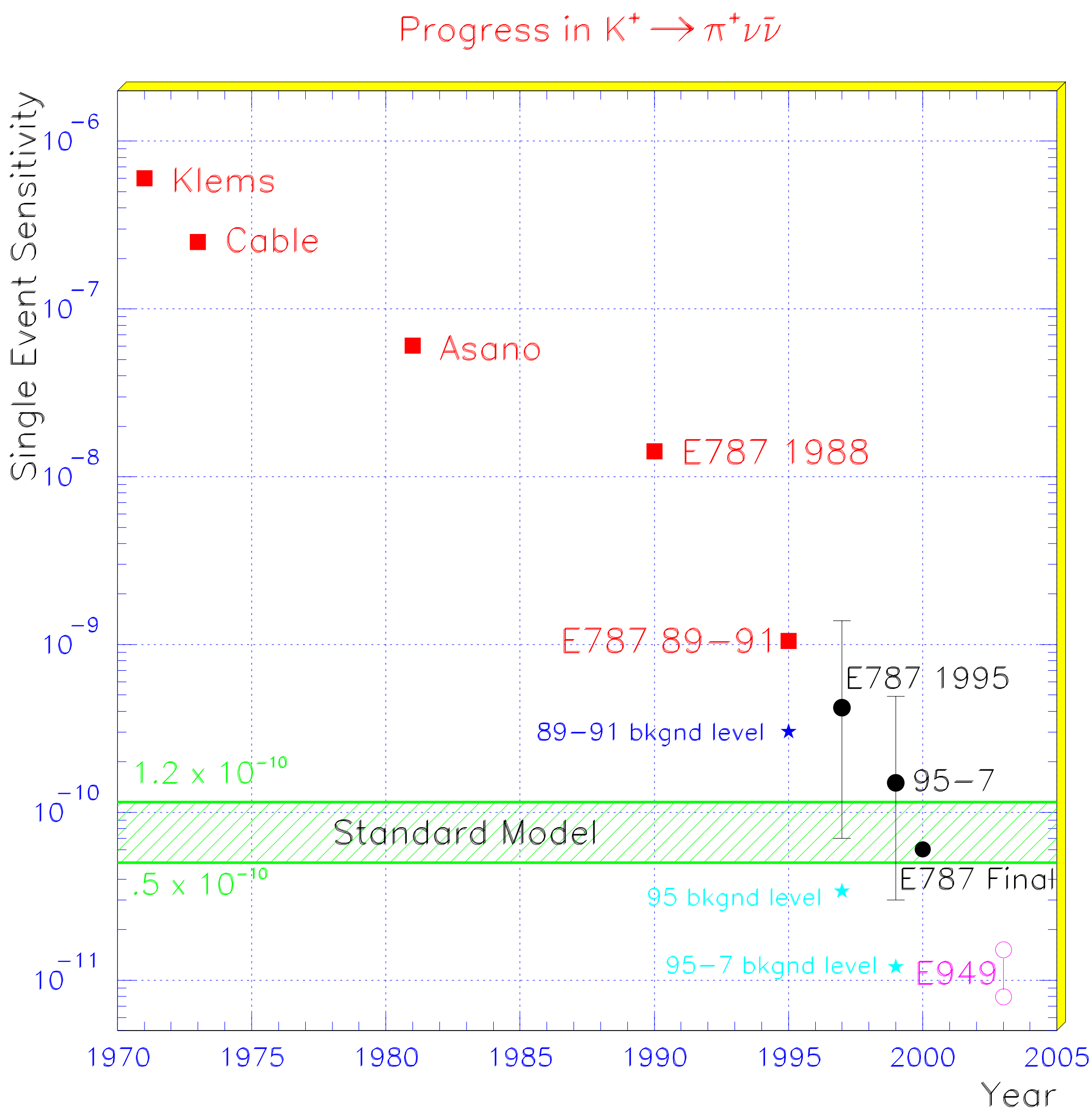


Sensitivity improvement with respect to E787 (1995):

- Increased spill length (×1.56)
- Lower momentum (×1.38)
- Increased efficiency (trigger, DAQ, analysis) (×3.2)
- Acc. below $K\pi2$ + higher rate analysis reopt. (×2)
- Total gain - ×14 per hour of data taking

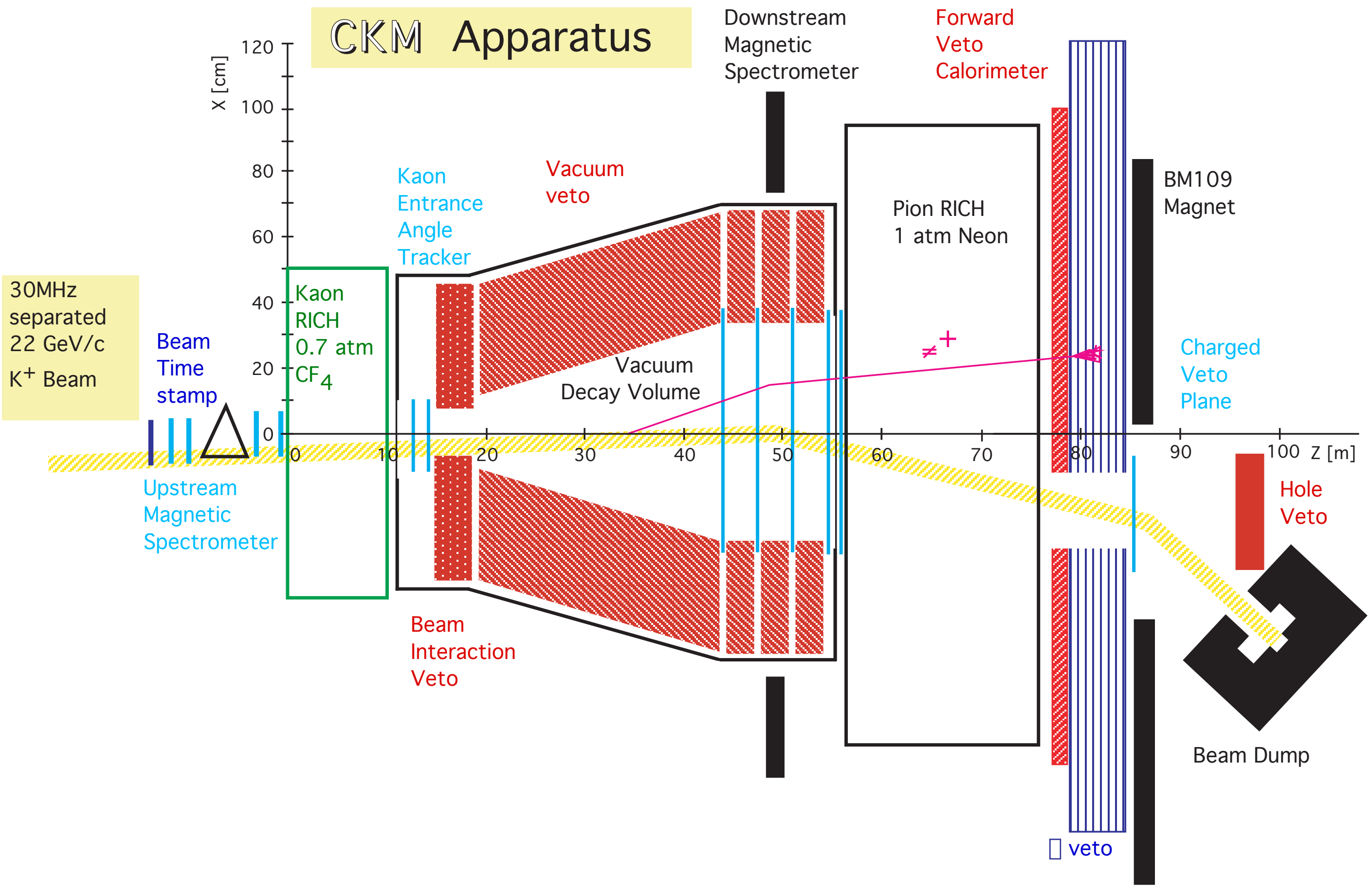
Progress in $K^+ \to \pi^+ \nu\bar{\nu}$

- E787 observed 1 event in 1995 run
- Analysis of 1995-7 data shows background rejection adequate for measurement at the S.M. level.
- Data collected in 1998 equal in sensitivity to previous total.
- Full E787 data sample (1995–98) will reach S.M. level.
- E949 should reach $\mathcal{O}(10^{-11}/evt)$ with ~ 10 S.M. events.

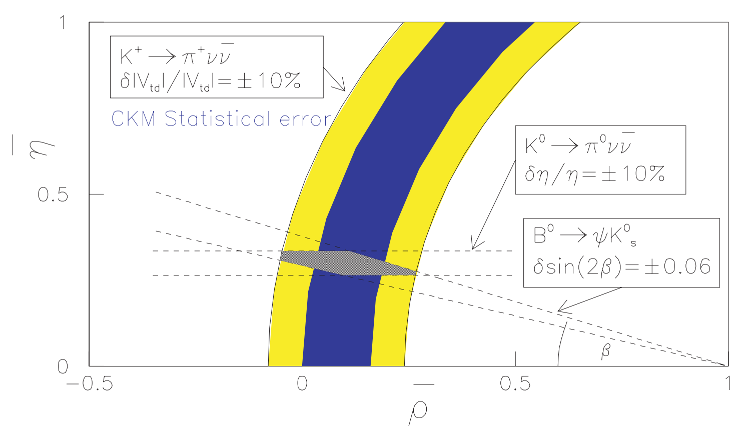


CKM Experiment to Measure $K^+ \to \pi^+ \nu \bar{\nu}$

New, in-flight technique:

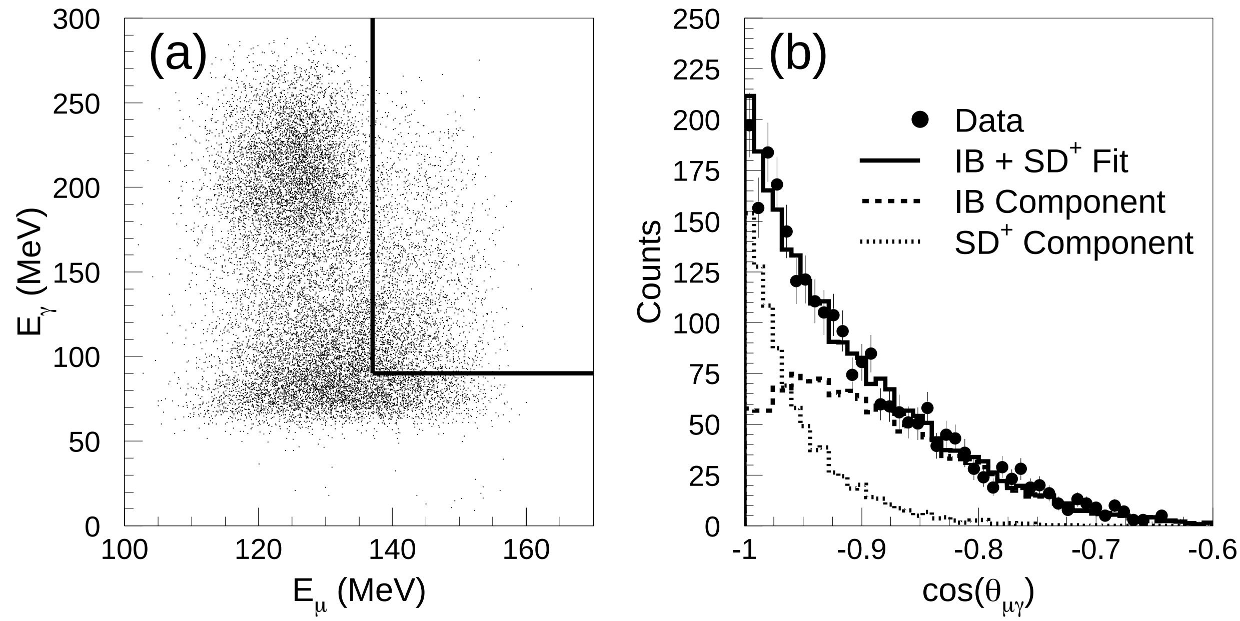


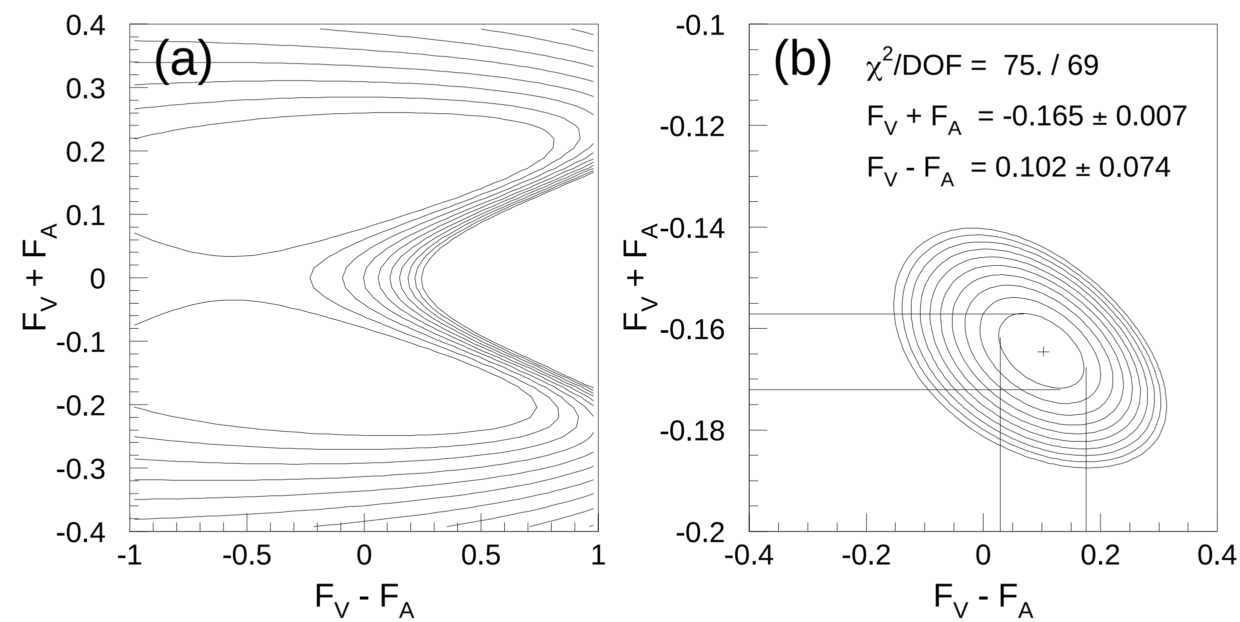
Reach for ~ 100 events:



E787 measurement of $K^+ \to \mu^+ \nu \gamma$

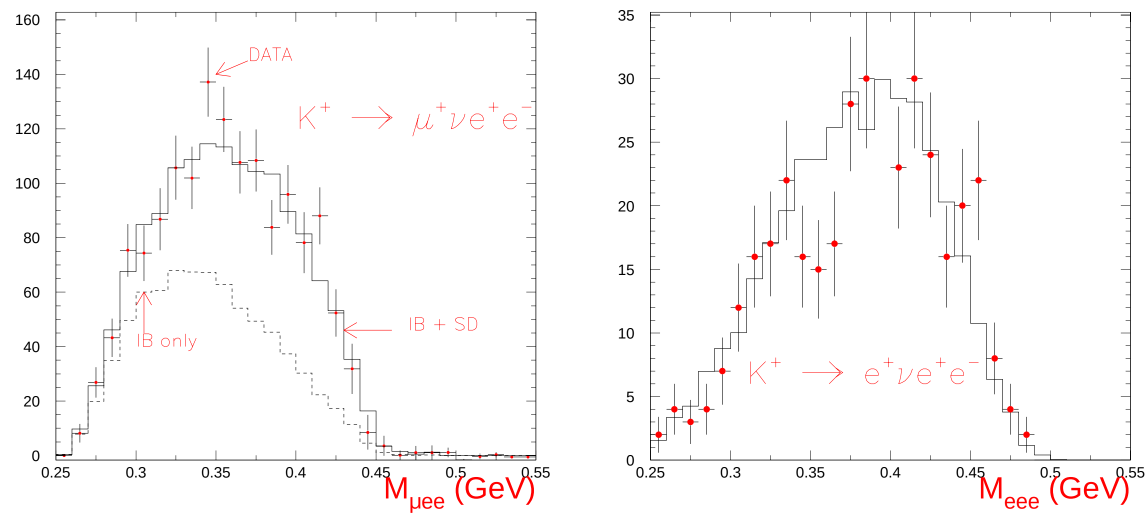
Object is to measure structure dependent radiation
Never seen before, but there is a Ch.P.T. prediction





From 900 events, find $|F_V + F_A| = 0.165 \pm 0.007 \pm 0.011$
$$F_V - F_A = 0.102 \pm 0.073 \pm 0.044$$
c.f. $\mathcal{O}(p^4)$ prediction $F_V + F_A = 0.137,\ F_V - F_A = 0.052$
Change by $< 1\sigma$ if q^2 variation allowed.

E865: Study of $K^+ \to \mu^+ \nu e^+ e^-$ and $K^+ \to e^+ \nu e^+ e^-$

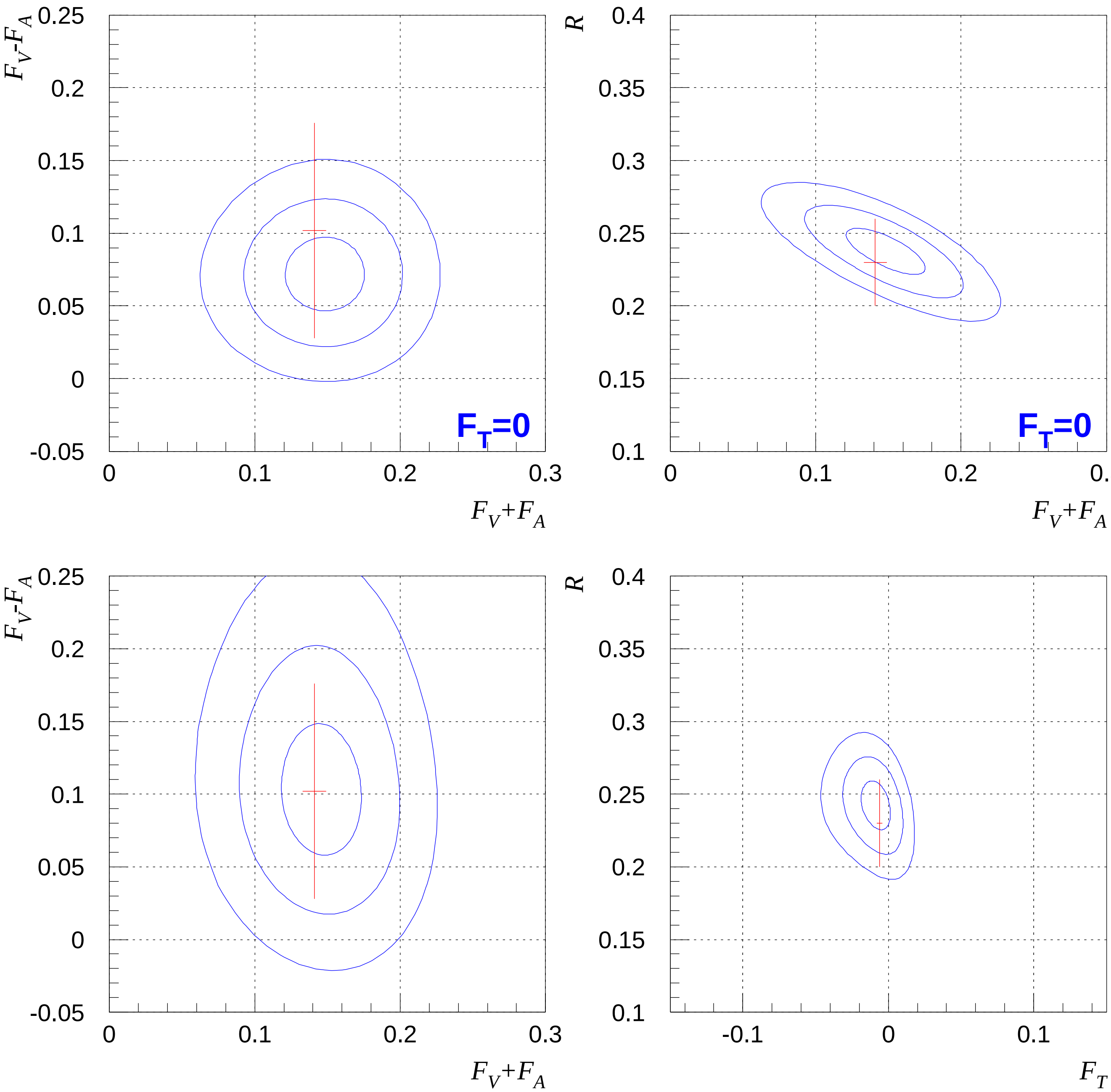


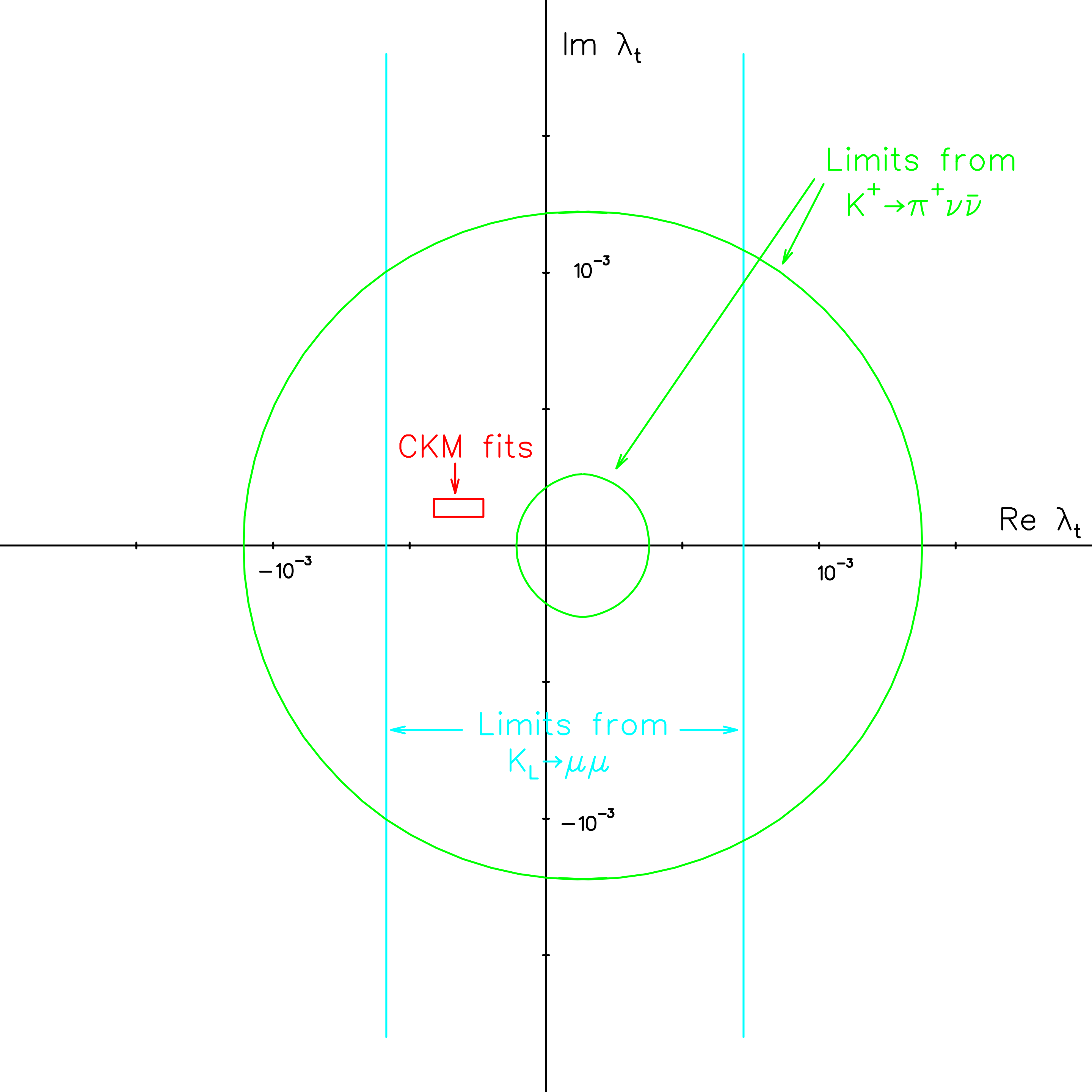
Left: μee mass distribution of $K^+ \to \mu^+ \nu e^+ e^-$ decays, in comparison with Monte Carlo with only inner bremsstrahlung, and with bremsstrahlung + structure dependent part;
Right: eee mass distribution of $K^+ \to e^+ \nu e^+ e^-$ decays, in comparison with Monte Carlo, which is dominated by the structure dependent part.

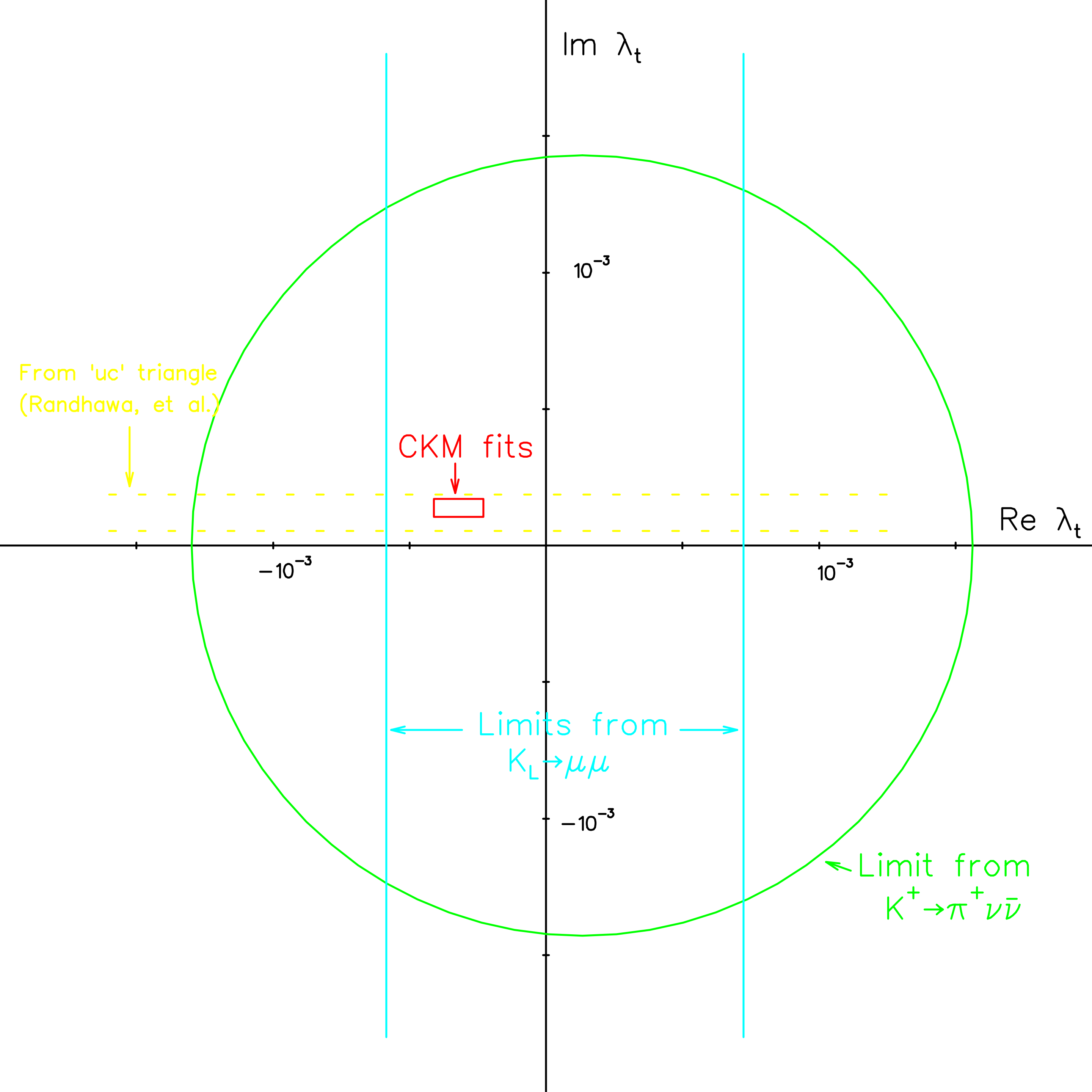
Decay Mode	Branching Ratio	Previous No. of Events	E865 No. of Events
$\mu^+ \nu e^+ e^-$	8×10^{-8}	14	1,500
$e^+ \nu e^+ e^-$	3×10^{-8}	4	350

- Measurement of Stucture dependent part of the Branching Ratios;
- First Measurement of electromagnetic form factor, R, in K^+ decay;
- Improved measurement of Vector and Axial vector form factors (F_V, F_A).

E865. $K^+ \to \mu^+ \nu e^+ e^-$ and $K^+ \to e^+ \nu e^+ e^-$




Im λ_t
Re λ_t
10^{-3}
-10^{-3}
10^{-3}
-10^{-3}
Limits from
$K^+ \to \pi^+ \nu \bar{\nu}$
CKM fits
Limits from
$K_L \to \mu\mu$


Im λ_t
Re λ_t
10^{-3}
-10^{-3}
10^{-3}
-10^{-3}
From 'uc' triangle
(Randhawa, et al.)
CKM fits
Limits from
$K_L \to \mu\mu$
Limit from
$K^+ \to \pi^+ \nu \bar{\nu}$

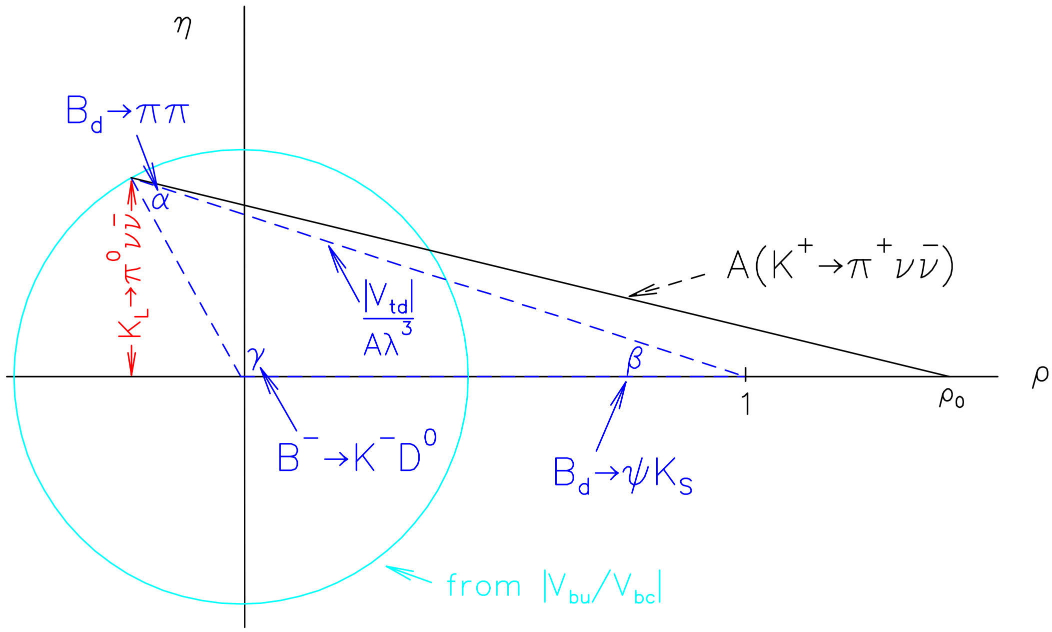
$K_L \to \pi^0 \nu \bar{\nu}$ in the Standard Model

Pure direct CP-violating (state-mixing very small)

Calculation in terms of fundamental parameters good to $\lesssim 2\%$

In terms of usual unitarity triangle parameterization:

$$B(K_L \to \pi^0 \nu \bar{\nu}) = 4 \cdot 10^{-10} A^4 \eta^2$$



Gives height of UT without triangulation

- with $K^+ \to \pi^+ \nu \bar{\nu}$ can determine ρ as well

Also note that

$$B(K_L \to \pi^0 \nu \bar{\nu}) = 1.56 \cdot 10^{-4} [Im(V_{ts}^* V_{td})]^2 \equiv 1.56 \cdot 10^{-4} [Im\lambda_t]^2$$

$Im\lambda_t$ presently triangulated to $\sim 22\%$,

- a dedicated experiment could directly measure it to $7 - 8\%$

There are only a few solid measurements on the UP

- none is better!

KTeV $K_L \to \pi^0 \nu\bar{\nu}$ using $\pi^0 \to e^+e^-\gamma$

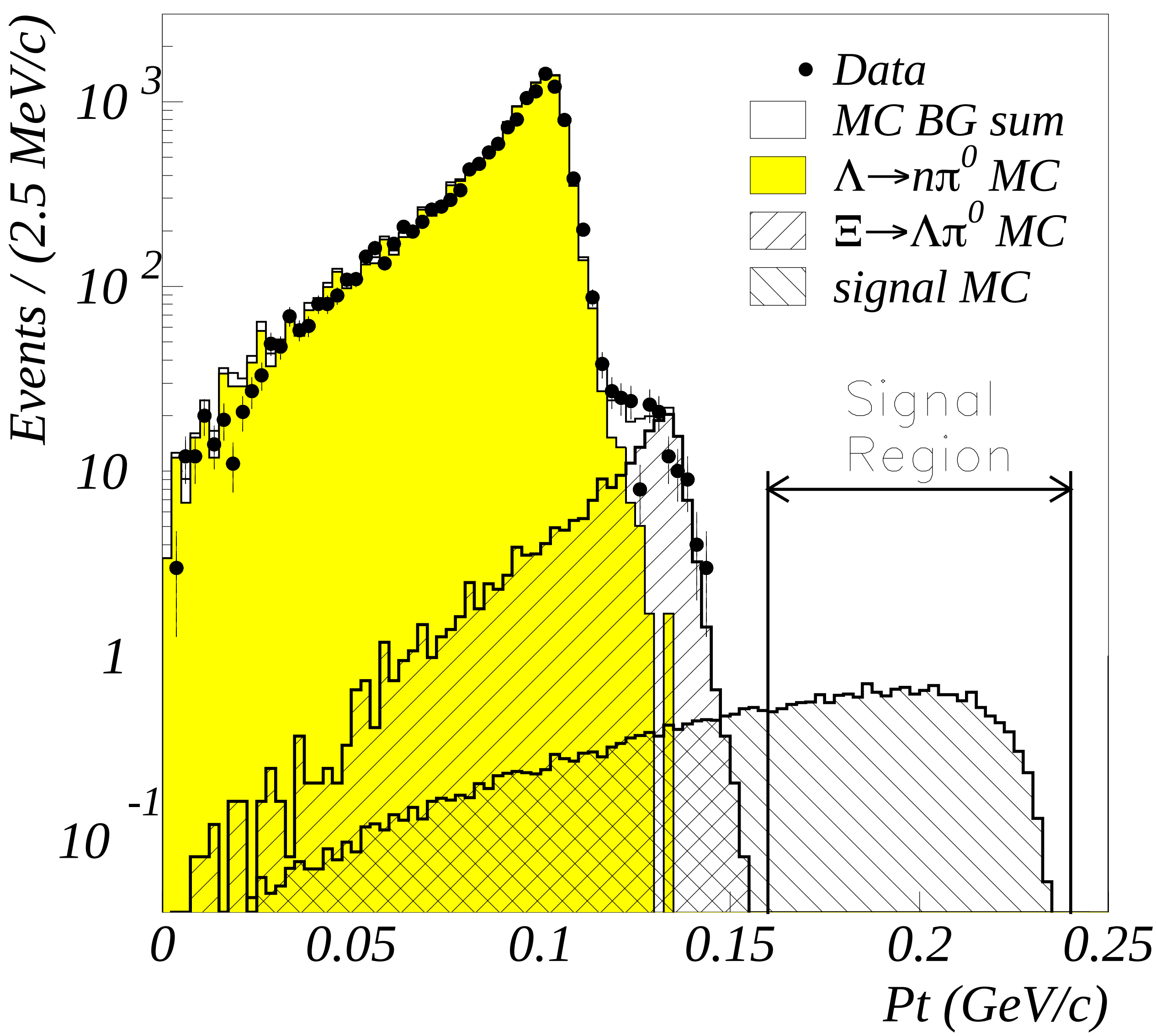
To be published in PRD (hep-ex/9907014).

Technique allows a vertex to be determined.

No events observed, $B\left(K_L \to \pi^0 \nu\bar{\nu}\right) < 5.9 \times 10^{-7}$ at 90% c.l.

Calculated background 0.04 events.

Estimate of ultimate reach $\sim 10^{-9}$.



A Model Independent Limit on $B(K_L \to \pi^0 \nu \bar{\nu})$

$B\left(K_L \to \pi^0 \nu \bar{\nu}\right) < 4.4 \times B\left(K^+ \to \pi^+ \nu \bar{\nu}\right)$

Proposed by Y. Grossman & Y. Nir

- Phys. Lett. **B398**, 163 (1007)

A consequence of $\Delta I = \frac{1}{2}$ rule

- trivial in SM

- true in for almost any short-distance interaction
  even if that interaction conserves CP

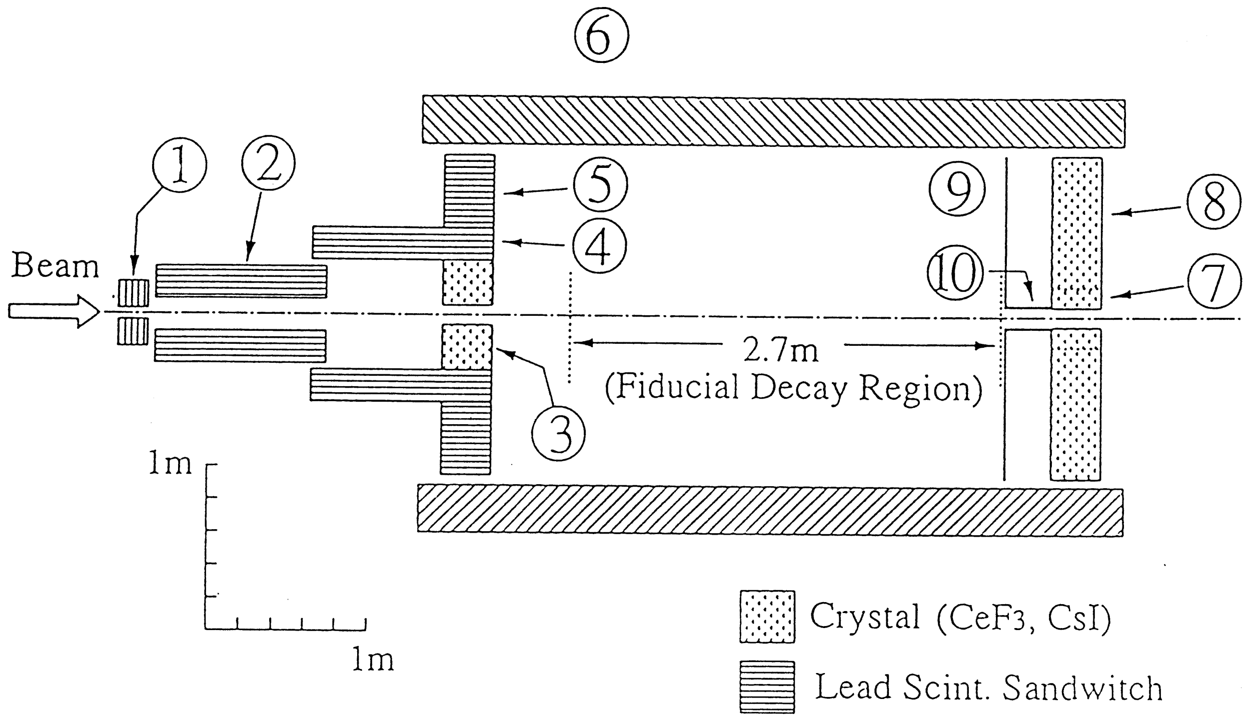
New E787 result is $B\left(K^+ \to \pi^+ \nu \bar{\nu}\right) = \left(1.5^{+3.4}_{-1.2}\right) \times 10^{-10}$

This leads to $B\left(K_L \to \pi^0 \nu \bar{\nu}\right) < 3.1 \times 10^{-9}$ at 95% c.l.

Far better than any other current limit

- but still 100 times larger than SM expectation

KEK E391a search for $K_L \to \pi^0 \nu \bar{\nu}$



Carefully designed "pencil" beam, compact detector

Entire apparatus in vacuum

Very high performance photon veto

Expected to reach $\sim 10^{-10}$ single event sensitivity
- *i.e.* $\sim 3\times$ S.M. prediction

Beamline construction & tuning in November 1999

Run start scheduled for 2001

Test bed for JHF experiment

KaMI $K_L \to \pi^0 \nu \bar{\nu}$

EOI (hep-ex/9709026), no proposal yet.

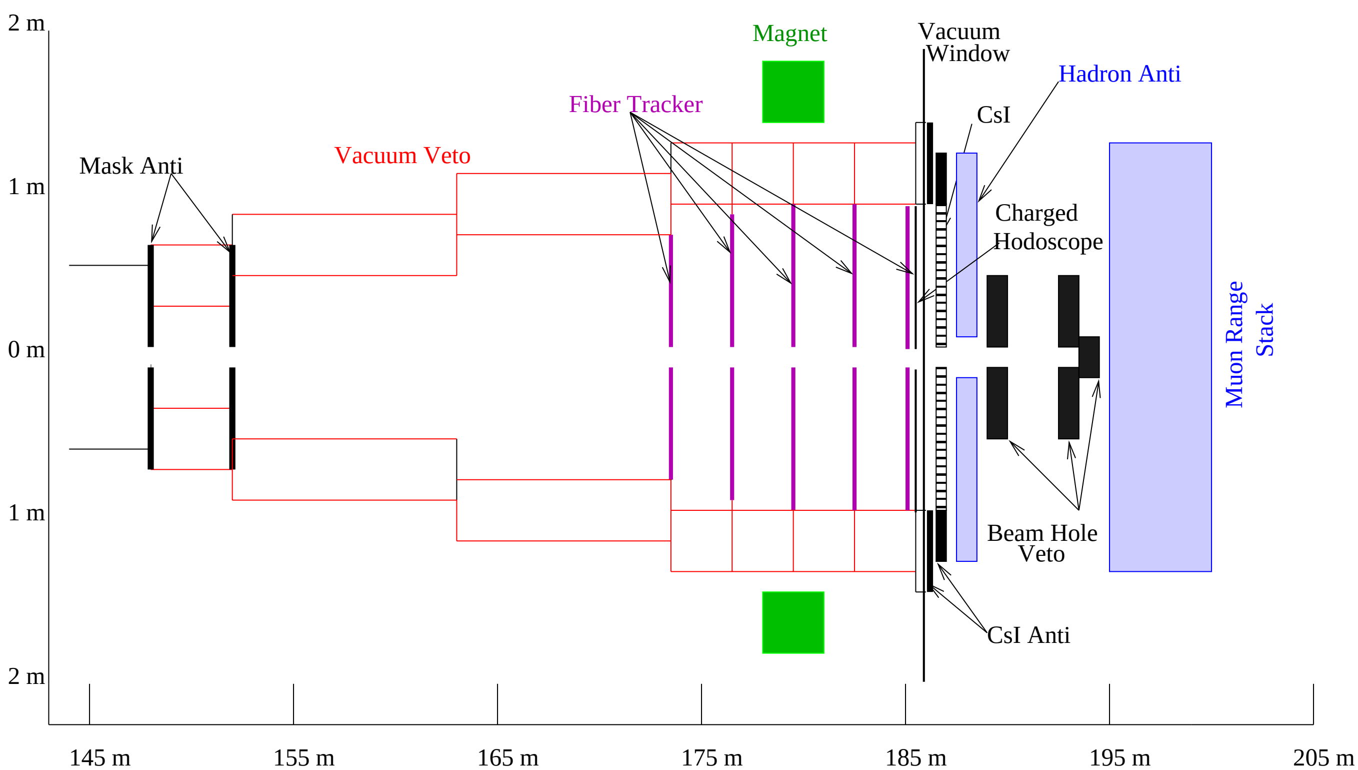
3×10^{13}/spill, 120 GeV proton beam at Main Injector.

Pencil beam, $\pi^0 \to \gamma\gamma$ decay

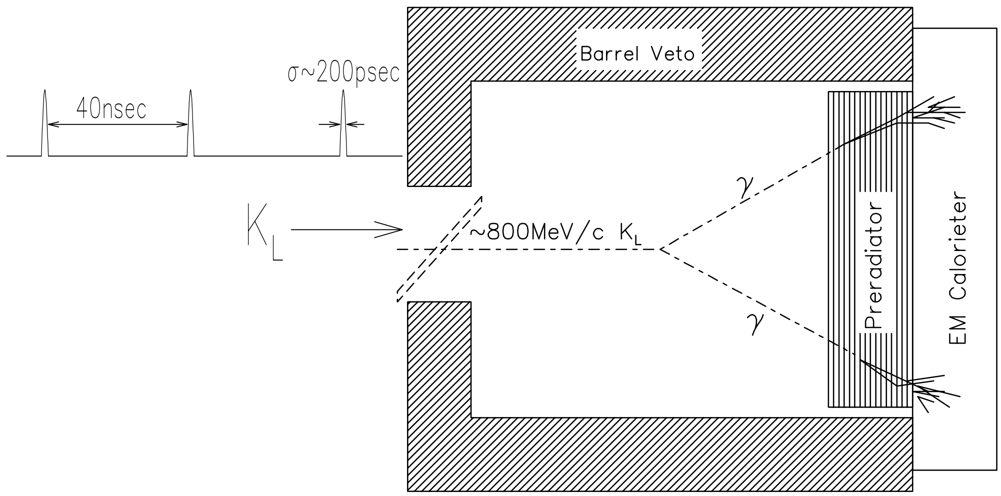
Recycled KTeV CsI array central

Eventually ~ 100 events, S:B $\sim 3:1$

KAMI DETECTOR LAYOUT



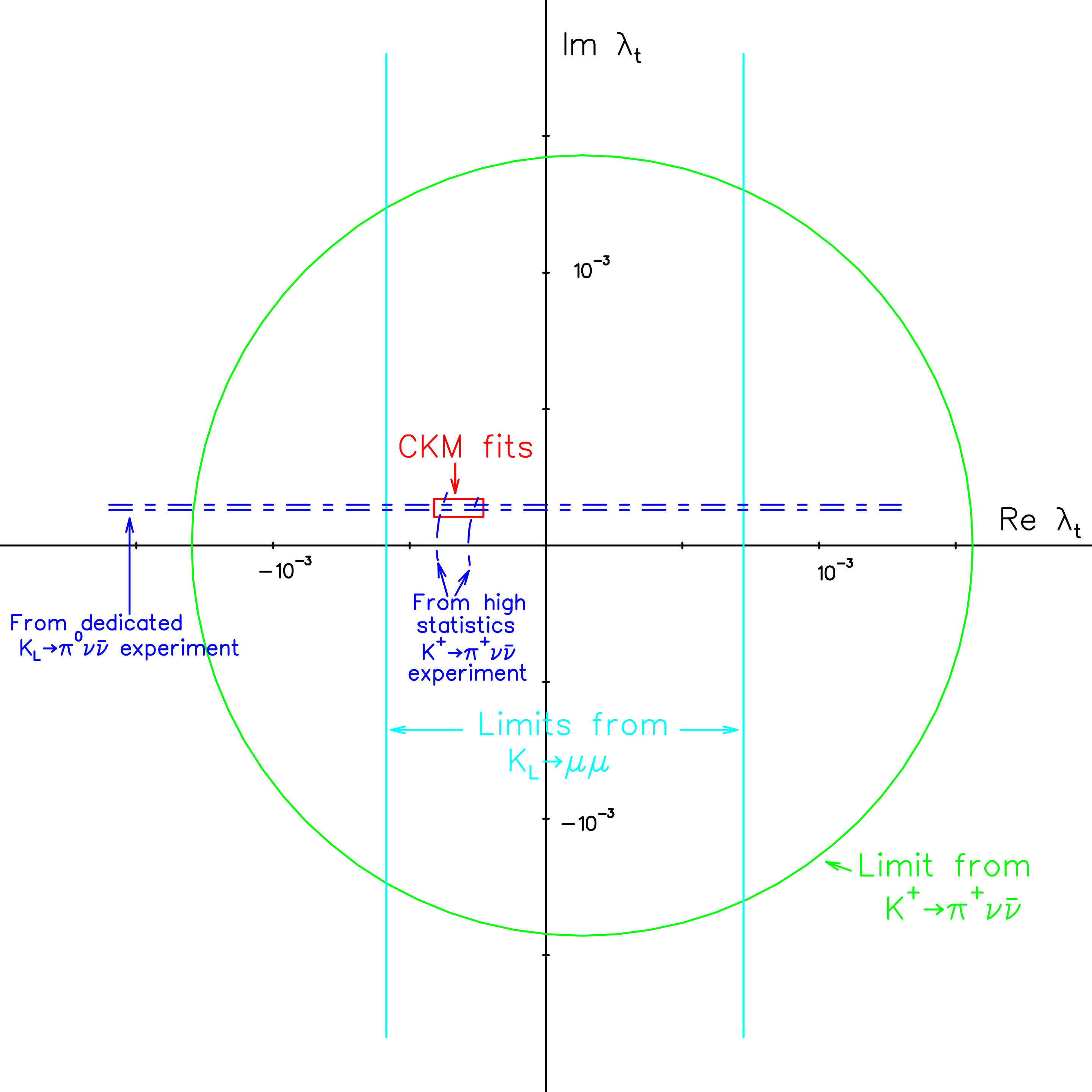
Principles of KOPIO



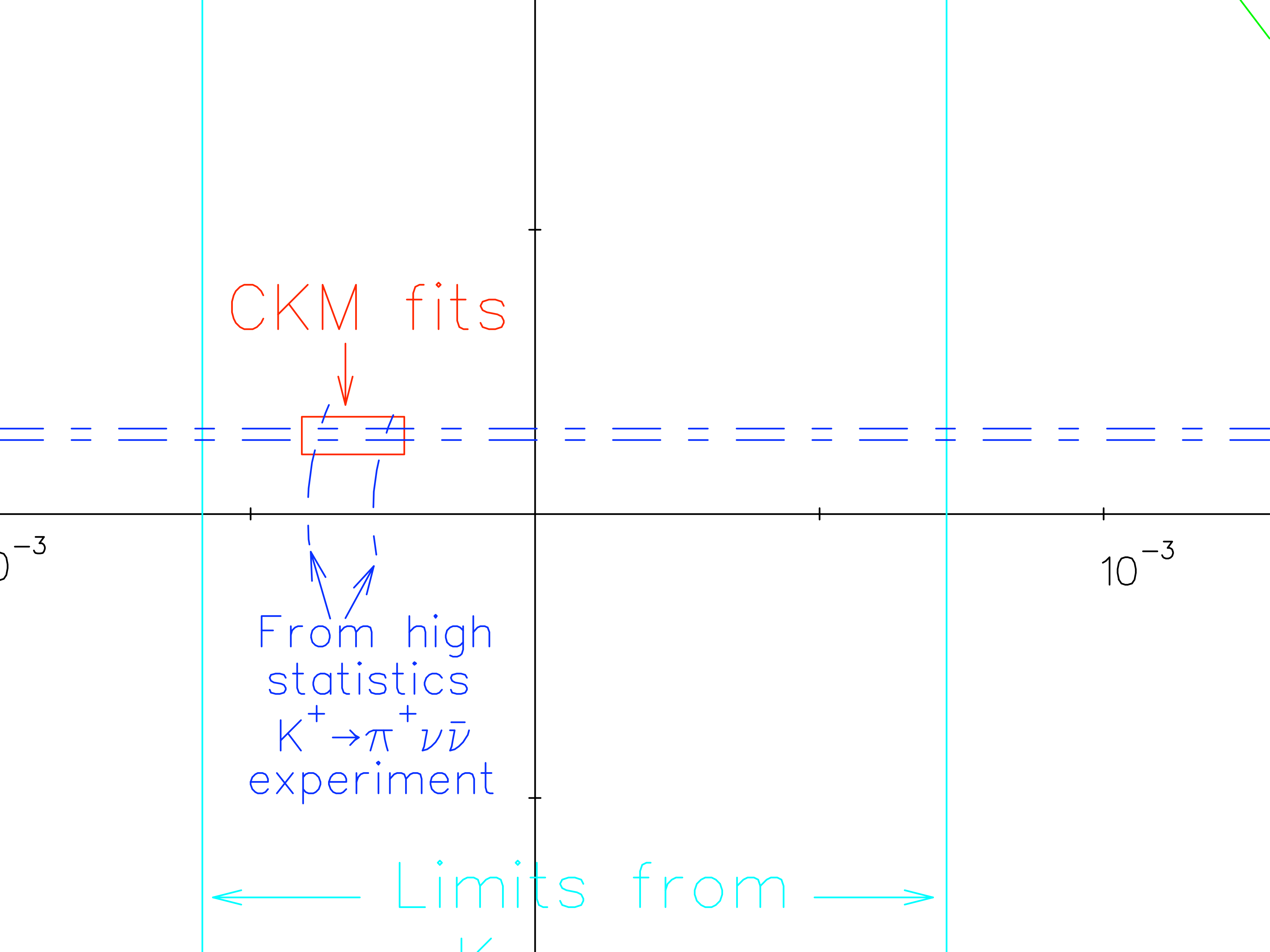
Work in the K_L center of mass system
All possible initial & final state quantities measured
Measure backgrounds
Veto hermetically

Microbunched, large angle (low energy) beam
Preradiator to measure γ directions
+ calorimeter, get energies, times
E787-type veto + beam catcher veto

Advantages:
- vertex positively determined
- 4C fit to π^0
- can require π^0 consistent with $K_L \to \pi^0 \nu\bar{\nu}$
- can avoid configuration with low energy missed γ's
- reduced bckgnd from K_L decay & other sources
- most neutrons, off-momentum K_L put out of time
- most n below π^0 production threshold
- no hyperons
- preradiator also serves as particle ID device



Im λ_t
Re λ_t
10^{-3}
-10^{-3}
10^{-3}
-10^{-3}
CKM fits
From dedicated
$K_L \to \pi^0 \nu\bar{\nu}$ experiment
From high
statistics
$K^+ \to \pi^+ \nu\bar{\nu}$
experiment
Limits from
$K_L \to \mu\mu$
Limit from
$K^+ \to \pi^+ \nu\bar{\nu}$



CKM fits
From high statistics $K^+ \to \pi^+ \nu \bar{\nu}$ experiment
10^{-3}
10^{-3}
Limits from

Conclusions

K decay section of the PDB is being entirely rewritten

LFV experiments have been pushed to remarkable sensitivities
- correspond to mass scale of well over 100 TeV
- observation of smallest BR in particle physics

But success has killed most models predicting LFV in K decay
- future mainly as by-products of other studies

High precision measurement of $K_L \to \mu^+\mu^-$ is made
- very useful if theoretical issues resolved
- auxilliary measurements to help this resolution in process

The motivation for pursuing $K \to \pi\nu\bar{\nu}$ stronger than ever
- "alternative" unitarity triangle can be constructed
- effects of non-SM physics different than for B sector

$K^+ \to \pi^+\nu\bar{\nu}$ has been seen,
- clear that it can be exploited
- two initiatives to pursue it further
    - 10^{-11}/evt level experiment is being prepared
    - 10^{-12}/evt level experiment in R&D phase

First dedicated experiment to seek $K_L \to \pi^0\nu\bar{\nu}$ proceeding
Two other initiatives in progress
- the groups are cooperating
- goal of making $\lesssim 15\%$ measurement of η

Future high precision determinations of λ_t from K's
can be compared to B information to critically test SM